Oil & Natural Gas Technology

DOE Award No.: DE-FC26-03NT15424

SEMI-ANNUAL
TECHNICAL PROGRESS REPORT
October 1, 2007 – March 31, 2008

THE MISSISSIPPIAN LEADVILLE LIMESTONE EXPLORATION PLAY, UTAH AND COLORADO – EXPLORATION TECHNIQUES AND STUDIES FOR INDEPENDENTS

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Prepared for:
United States Department of Energy
National Energy Technology Laboratory

July 2008

Office of Fossil Energy

DISCLAIMER

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Contract No. DE-FC26-03NT15424

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ABSTRACT

The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil/condensate from seven fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent producers operate and continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risks, especially in environmentally sensitive areas, and add new oil discoveries and reserves.

This report covers research and technology transfer activities for the first half of the fifth project year (October 1, 2007, through March 31, 2008), Budget Period II. Research consisted of determining the regional hydrodynamic trends in the Mississippian of the Paradox Basin, Utah and Colorado, and how they affected hydrocarbon migration. Shut-in drillstem test (DST) pressure data from petroleum exploration and development wells in the Paradox Basin established the major hydrodynamic trends, especially within the Mississippian. With the exception of the eastern edge of the basin, there is one pressure regime for the Mississippian with a composite pressure gradient of 0.47 pounds per square inch/foot (10.6 kPa/m) over an elevation range of +4000 to -10,000 feet (1200 to -3000 m) above sea level (ft asl [m asl]). This remarkably uniform pressure regime over an area of at least 100 by 100 square miles (260 by 260 km^2) indicates relatively high permeability within the Mississippian. The gradient is about 10% above hydrostatic for fresh water. The head is between 3800 and 4000 ft asl (1160 and 1200 m asl), and coincides with the elevation of the lower Green River and Cataract Canyon section of the Colorado River where they traverse the basin. It appears that the Mississippian and older reservoirs across most of the Paradox Basin are in good hydrological communication with the Colorado River system. This large-scale hydrological connection between the surface and the Mississippian may be a geologically recent occurrence. Consideration of the rate of incision by the Colorado River system suggests that the Mississippian could have been hydrologically isolated and fully saturated several million years ago, and could have held significantly greater quantities of oil and gas.

Technology transfer activities for the reporting period consisted of exhibiting a booth display of project materials at the 2007 Rocky Mountain Section Meeting of the American Association of Petroleum Geologists (AAPG), a technical presentation and core workshop, and publications. An abstract identifying potential oil-prone areas based on hydrocarbon shows using epifluorescence techniques was submitted and accepted for presentation at the July 2008 AAPG Rocky Mountain Section meeting in Denver, Colorado. The project home page was updated on the Utah Geological Survey Web site.

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EXECUTIVE SUMMARY

The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil/condensate from seven fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. These fields are currently operated by independent producers. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent operators continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville Limestone, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risk especially in environmentally sensitive areas, and add new oil discoveries and reserves.

To achieve this goal and carry out the Leadville Limestone study, the Utah Geological Survey (UGS) and Eby Petrography & Consulting, Inc., have entered into a cooperative agreement with the U.S. Department of Energy (DOE), National Energy Technology Laboratory, Tulsa, Oklahoma. The research is funded as part of the DOE Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. This report covers research and technology transfer activities for the first half of the fifth project year (October 1, 2007, through March 31, 2008), Budget Period II. Research consisted of determining the regional hydrodynamic trends in the Mississippian of the Paradox Basin, Utah and Colorado, and how they affected hydrocarbon migration.

Shut-in drillstem test (DST) pressure data from petroleum exploration and development wells in the Paradox Basin were reviewed to establish the major hydrodynamic trends, especially within the Mississippian. Although about 5000 DST results have been reported, the dataset is very noisy and screening criteria were needed to upgrade it. This resulted in 1529 potentially useable DSTs for the basin, of which 395 DSTs are for the Mississippian and older formations. With the exception of the eastern edge of the basin (western flanks of the San Juan Mountains), there is a single pressure regime for the Mississippian, having a composite pressure gradient of 0.47 pounds per square inch/foot (10.6 kPa/m) over an elevation range of +4000 to -10,000 feet (1200 to -3000 m) above sea level (ft asl [m asl]). This remarkably uniform pressure regime over an area of at least 100 by 100 square miles (260 by 260 km^2) indicates relatively high permeability within the Mississippian. The gradient is about 10% above hydrostatic for fresh water, but is consistent with the density of relatively saline water with a total dissolved solids concentration of 100,000 to 150,000 mg/kg. The head is between 3800 and 4000 ft asl (1160 and 1200 m asl), and coincides with the elevation of the lower Green River and Cataract Canyon section of the Colorado River where they traverse the basin. It appears that the Mississippian and older reservoirs across most of the Paradox Basin are in good hydrological communication with the Colorado River system, perhaps because they are within about 1000 ft (300 m) of the surface beneath Cataract Canyon. This large-scale hydrological connection between the surface and the Mississippian may be a geologically recent occurrence. Consideration of the rate of incision by the Colorado River system suggests that the Mississippian could have been hydrologically isolated and fully saturated several million years ago, and could have held significantly greater quantities of oil and gas.

Technology transfer activities for the reporting period consisted of a convention exhibit booth display, a technical presentation and core workshop, and publications. Project materials,

plans, objectives, and results were displayed at the Utah Geological Survey exhibit booth during the American Association of Petroleum Geologists (AAPG) Rocky Mountain Section (RMS) meeting, October 7-9, 2007, in Snowbird, Utah. A Leadville core workshop was presented in conjunction with the meeting. Twenty-two attendees examined core from Lisbon field in terms of both facies and diagenesis. A presentation was also made at the AAPG RMS meeting summarizing the Leadville project and the surface geochemical survey in the Lisbon field area. Project team members published abstracts and a Semi-Annual Technical Progress Report detailing project work, results, and recommendations. An abstract identifying potential oil-prone areas based on hydrocarbon shows using epifluorescence techniques was submitted and accepted for presentation at the July 2008 AAPG RMS meeting in Denver, Colorado. The project home page was updated on the Utah Geological Survey Web site.

INTRODUCTION

Project Overview

The Mississippian Leadville Limestone has produced over 53 million barrels (bbls) (8.4 million m^3) of oil/condensate from seven fields in the northern Paradox Basin region, referred to as the Paradox fold and fault belt, of Utah and Colorado (figure 1). All of these fields are currently operated by independent producers. There have been no significant new oil discoveries since the early 1960s, and only independent producers continue to explore for Leadville oil targets in the region, 85% of which is under the stewardship of the federal government. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored with only about 100 exploratory wells that penetrated the Leadville (less than one well per township), and thus the potential for new discoveries remains great.

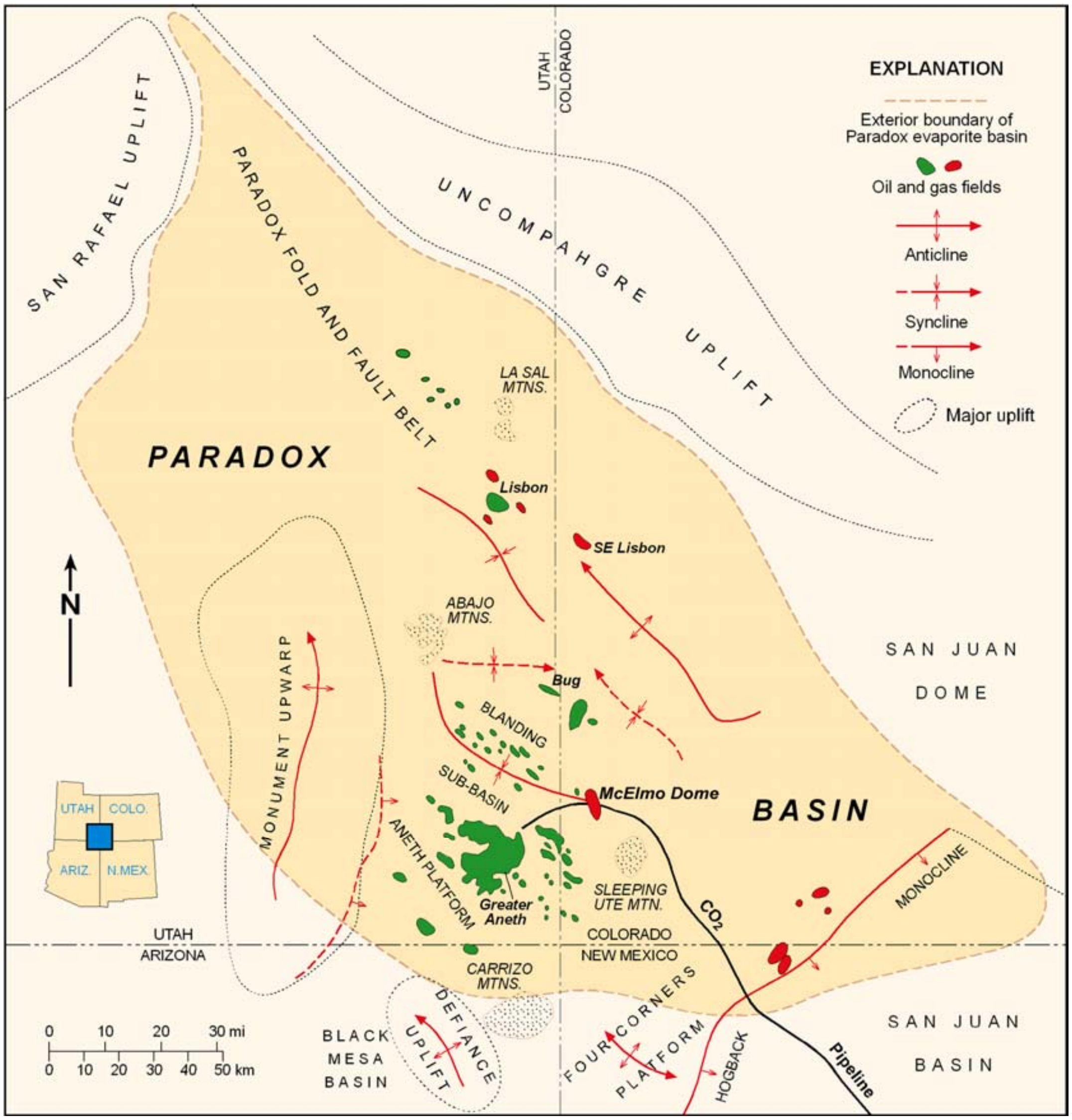


Figure 1. Regional setting and oil and gas fields in the Paradox Basin of Utah, Colorado, Arizona, and New Mexico (modified from Harr, 1996).

The overall goals of this study are to (1) develop and demonstrate techniques and exploration methods never tried on the Leadville Limestone, (2) target areas for exploration, (3) increase deliverability from new and old Leadville fields through detailed reservoir characterization, (4) reduce exploration costs and risk especially in environmentally sensitive areas, and (5) add new oil discoveries and reserves.

The Utah Geological Survey (UGS) and Eby Petrography & Consulting, Inc. have entered into a cooperative agreement with the U.S. Department of Energy (DOE) as part of its Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. The project is being conducted in two phases, each with specific objectives and separated by a continue-stop decision point based on results as of the end of Phase I (Budget Period I). The objective of Phase I was to conduct a case study of the Leadville reservoir at Lisbon field (the largest Leadville oil producer in the Paradox Basin), San Juan County, Utah, in order to understand the reservoir characteristics and facies that can be applied regionally. Phase I has been completed and Phase II (Budget Period II) approved by DOE. The first objective of Phase II is to conduct a low-cost field demonstration of new exploration technologies to identify potential Leadville oil migration directions (evaluating the middle Paleozoic hydrodynamic pressure regime) and surface geochemical anomalies, especially in environmentally sensitive areas. The second objective is to determine regional facies (evaluating cores, geophysical well logs, outcrop, and modern analogs), identify potential oil-prone areas, and target areas for Leadville exploration.

These objectives are designed to assist the independent producers and explorers who have limited financial and personnel resources. All project maps, studies, and results are, or will be, publicly available in digital (interactive, menu-driven products on compact disc) or hard-copy format and presented to the petroleum industry through a proven technology transfer plan. The technology transfer plan includes a Technical Advisory Board composed of industry representatives operating in the Paradox Basin and a Stake Holders Board composed of representatives of state and federal government agencies, and groups with a financial interest within the study area. Project results are, or will be disseminated, via the UGS Web site, technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, convention displays, papers in various technical or trade journals, and UGS publications.

This report covers research and technology transfer activities for the first half of the fifth project year (October 1, 2007, through March 31, 2008), Budget Period II. Research consisted of determining the regional hydrodynamic trends in the Mississippian of the Paradox Basin, Utah and Colorado, and how they affected hydrocarbon migration.

Project Benefits and Potential Application

Exploring the Leadville Limestone is high risk, with less than a 10% chance of success based on the drilling history of the region. Prospect definition often requires expensive, three-dimensional (3D) seismic acquisition, at times in environmentally sensitive areas. These facts make exploring difficult for independents that have limited funds available to try new, unproven techniques that might increase the chance of successfully discovering oil. We believe that one or more of the project activities will reduce the risk taken by an independent producer in looking for Leadville oil, not only in exploring but in using a new technique. For example, the independent would not likely attempt surface geochemical surveys without first knowing they have been proven successful in the region. Our project proves geochemical surveys are an effective technique in environmentally sensitive areas, thus saving independents both time and money exploring for Leadville oil.

Another problem in exploring for oil in the Leadville Limestone is the lack of published or publicly available geologic and reservoir information, such as regional facies maps, complete reservoir characterization studies, surface geochemical surveys, regional hydrodynamic pressure regime maps, and oil show data and migration interpretations. This project provides this information to save independents cash and manpower resources which they simply do not possess or normally have available only for drilling. The technology, maps, and studies generated from this project will help independents to identify or eliminate areas and exploration targets prior to spending significant financial resources on seismic data acquisition and potential environmental litigation, and therefore increase the chance of successfully finding new economic accumulations of Leadville oil.

These benefits may also apply to other high-risk, sparsely drilled basins or regions where there are potential shallow-marine carbonate reservoirs equivalent to the Mississippian Leadville Limestone. These areas include the Utah-Wyoming-Montana thrust belt (Madison Limestone), the Kaiparowits Basin in southern Utah (Redwall Limestone), the Basin and Range Province of Nevada and western Utah (various Mississippian and other Paleozoic units), and the Eagle Basin of Colorado (various Mississippian and other Paleozoic units).

Many mature basins have productive carbonate reservoirs of shallow-marine shelf origin. These mature basins include the Eastern Shelf of the Midland Basin, West Texas (Pennsylvanian-age reservoirs in the Strawn, Canyon, and Cisco Formations); the Permian Basin, West Texas and southeast New Mexico (Permian-age Abo and other formations along the northwest shelf of the Permian Basin); and the Illinois Basin (various Silurian units). A successful demonstration in the Paradox Basin makes it very likely that the same techniques could be applied in other basins as well. In general, the average field size in these other mature basins is larger than fields in the Paradox Basin. Even though there are differences in depositional facies and structural styles between the Paradox Basin and other basins, the fundamental use of this project’s techniques and methods is a critical commonality.

PARADOX BASIN – OVERVIEW

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado, with small portions in northeastern Arizona and the northwestern corner of New Mexico (figure 1). The Paradox Basin is an elongate, northwest-southeast-trending, evaporitic basin that predominately developed during the Pennsylvanian, about 330 to 310 million years ago (Ma). The basin can generally be divided into three areas: the Paradox fold and fault belt in the north, the Blanding sub-basin in the south-southwest, and the Aneth platform in southeasternmost Utah (figure 1). The Mississippian Leadville Limestone is one of two major oil and gas reservoirs in the Paradox Basin, the other being the Pennsylvanian Paradox Formation (figure 2); minor amounts of oil are produced from the Devonian McCracken Sandstone at Lisbon field. Most Leadville production is from the Paradox fold and fault belt (figure 3).

The most obvious structural features in the basin are the spectacular anticlines that extend for miles in the northwesterly trending fold and fault belt. The events that caused these and many other structural features to form began in the Proterozoic, when movement initiated

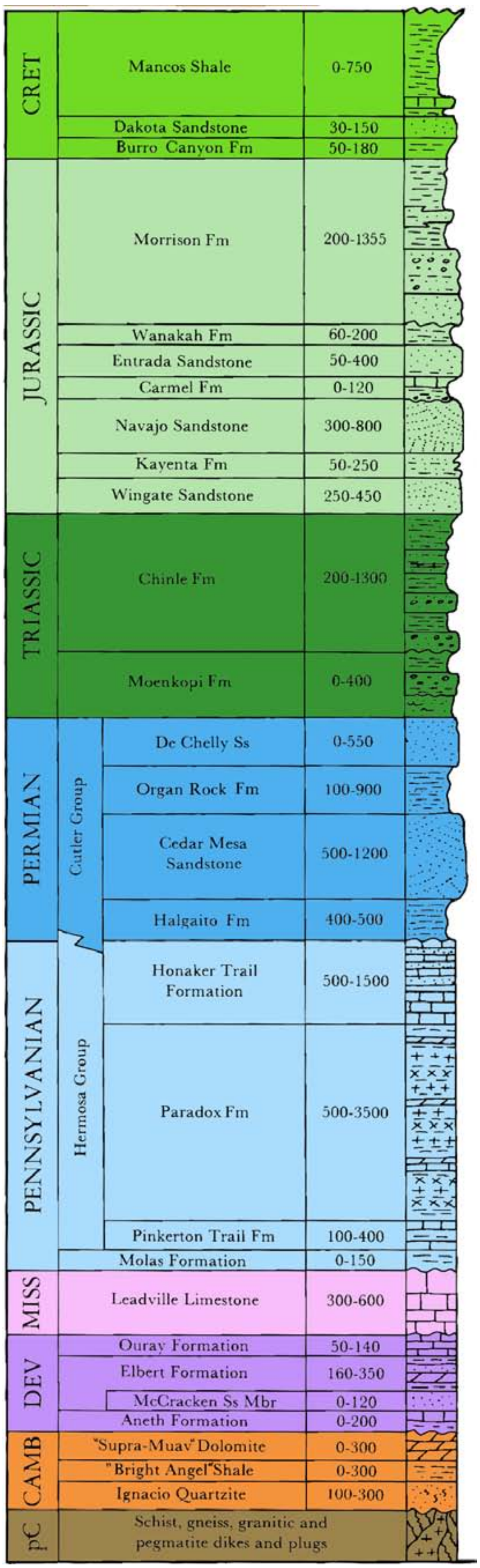


Figure 2. Stratigraphic section for the central Paradox Basin near Monticello, Utah (after Hintze, 1993).

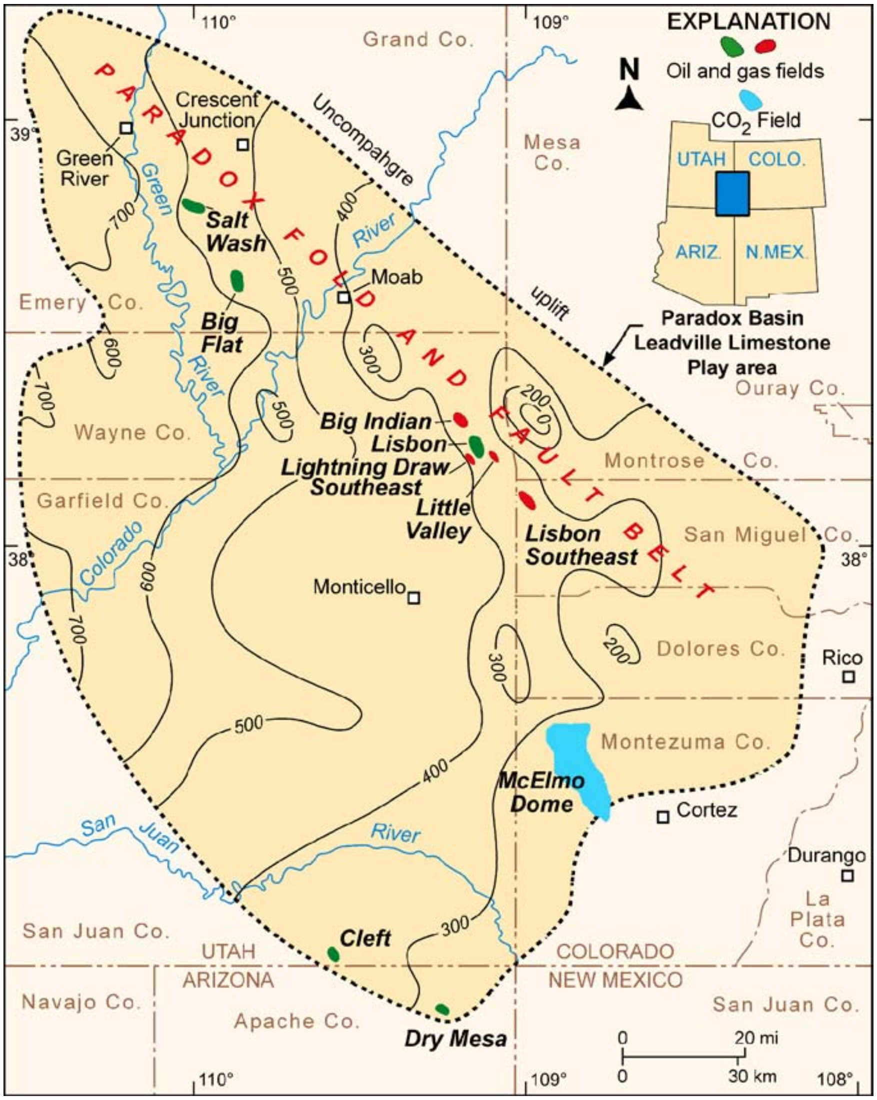


Figure 3. Regional setting of the Paradox Basin, showing oil and gas fields that produce from the Mississippian Leadville Limestone, and thickness of the Leadville (contour interval is 100). Modified from Parker and Roberts (1963).

on high-angle basement faults around 1700 to 1600 Ma (Stevenson and Baars, 1986, 1987). During Cambrian through Mississippian time, this region, as well as most of eastern Utah, was the site of typical thin, marine deposition on the craton while thick deposits accumulated in the miogeocline to the west (Hintze, 1993). However, major changes began in the Pennsylvanian when a pattern of basins and fault-bounded uplifts developed from Utah to Oklahoma as a consequence of the collision of South America, Africa, and southeastern North America (Kluth and Coney, 1981; Kluth, 1986), or from a smaller-scale collision of a microcontinent with south-central North America (Harry and Mickus, 1998). One result of this tectonic event was the uplift of the Ancestral Rockies in the western United States. The Uncompahgre Highlands (uplift) in eastern Utah and western Colorado initially formed as the westernmost range of the Ancestral Rockies during this ancient mountain-building period.

The Uncompahgre Highlands are bounded along their southwestern flank by a large, basement-involved, high-angle reverse fault identified from seismic surveys and exploration drilling (Frahme and Vaughn, 1983). As the highlands rose, an accompanying depression, or foreland basin, formed to the southwest — the Paradox Basin. Rapid subsidence, particularly during the Pennsylvanian and continuing into the Permian, accommodated large volumes of evaporitic and marine sediments that intertongue with non-marine arkosic material shed from the highland area to the northeast (Hintze, 1993).

The present Paradox Basin includes or is surrounded by other uplifts that formed during the Late Cretaceous-early Tertiary Laramide orogeny, such as the Monument upwarp in the west-southwest, and the Uncompahgre uplift, corresponding to the earlier Uncompahgre Highlands, forming the northeast boundary (figure 1). Oligocene laccolithic intrusions form the La Sal and Abajo Mountains in the north and central parts of the basin in Utah while the Carrizo Mountains in Arizona, and the Ute, La Plata, and San Miguel Mountains in Colorado were intruded along the southeastern boundary of the basin (figure 1).

The area now occupied by the Paradox fold and fault belt was also the site of greatest Pennsylvanian/Permian subsidence and salt deposition. Folding in the Paradox fold and fault belt began as early as the Late Pennsylvanian as sediments were laid down thinly over areas of rising salt and thickly in areas between rising salt (Doelling, 2000). The Paradox fold and fault belt formed during the Late Cretaceous through Quaternary by a combination of (1) reactivation of basement normal faults, (2) additional salt flowage followed by dissolution and collapse, and (3) regional uplift (Doelling, 2000). Outcrops ranging in age from Pennsylvanian through Cretaceous, with surficial Quaternary deposits, are found within the Paradox Basin.

Most oil and gas produced from the Leadville Limestone is found in basement-involved, northwest-trending structural traps with closure on both anticlines and faults (figure 4). Lisbon, Big Indian, Little Valley, Lightning Draw Southeast, and Lisbon Southeast fields (figure 3) are sharply folded anticlines that close against the Lisbon or nearby fault zones. Salt Wash and Big Flat fields (figure 3), northwest of the Lisbon area, are unfaulted, east-west- and north-south-trending anticlines, respectively.

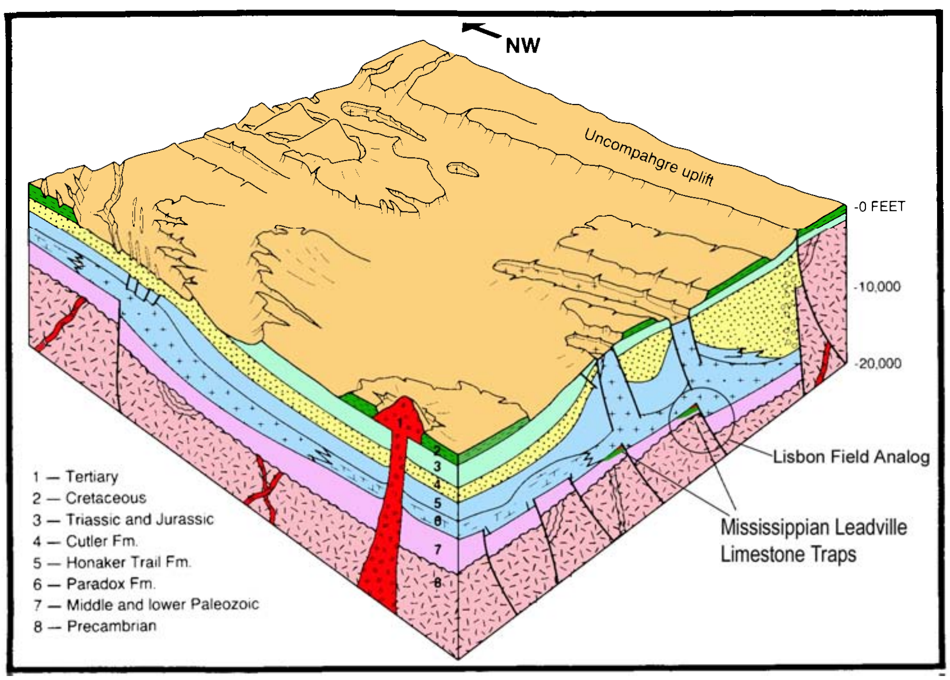


Figure 4. Schematic block diagram of the Paradox Basin displaying basement-involved structural trapping mechanisms for the Leadville Limestone fields (modified from Petroleum Information, 1984; original drawing by J.A. Fallin).

REGIONAL MIDDLE PALEOZOIC HYDRODYNAMIC PRESSURE REGIME, PARADOX BASIN, UTAH – RESULTS AND DISCUSSION

Introduction

Recently there has been increased interest in exploring for potential reservoirs of oil and gas in Mississippian rocks of the Paradox Basin. Although most oil in the basin has been found in carbonate buildups (algal mounds) of the Pennsylvanian, the northwest-trending fold and fault belt near the northern margin of the basin contains several Mississippian oil and gas fields, the largest being Lisbon, Utah (figure 3). McElmo Dome, southwest Colorado, near the southeast margin of the basin is a major producer of carbon dioxide (CO_2) from the Mississippian (Gerling, 1983; Tremain, 1993). Two minor oil fields (abandoned) occur near the southern margin of the basin, close to the Utah-Arizona state line.

One factor providing insight to recent secondary or tertiary migration of oil within the Mississippian is the present hydrodynamic condition. A horizontal pressure gradient within relatively permeable reservoir rock may indicate significant water movement that displaces trapped oil, whereas abnormally high pressures could indicate hydrocarbon generation and accumulation in relatively low-permeability rocks.

The only prior systematic compilation of pressure trends within the Mississippian system of the Paradox Basin appears to be by Hanshaw and Hill (1969). They studied the potentiometric trends in seven "aquifers" ranging in age between the Cambrian-Devonian and the Permian. Their potentiometric map for the Mississippian (reproduced as figure 5) shows a head gradient of about 2400 ft (730 m) between the Utah-Colorado state line and east margin of the Paradox Basin adjacent to the San Juan Mountains (that is, head increasing eastwards). This was interpreted as a major recharge area in the vicinity of the mountains. An area to the southwest of the Abajo Mountains near the northern end of the Monument upwarp (figure 1) is shown as having more than 1000 ft (300 m) of head above the surrounding region of southeast Utah. The authors noted that hydrology here is complicated, with mixed evidence of oil wells that were dry to at least the Mississippian, and other wells that indicated an elevated water column.

The compilation by Hanshaw and Hill (1969) has several limitations which were acknowledged by the authors at that time. Firstly, it is dependent on analysis of only about 600 drillstem tests (DSTs) supplied by oil companies from wells drilled up until 1961. Of these, about 300 were usable, so the number of DSTs for a particular horizon's potentiometric map is presumably a small fraction of these. Unfortunately, the maps do not show the data points used to constrain the contours. Secondly, the authors chose to present the pressure measurements in the form of a potentiometric surface obtained by converting the pressure to a freshwater column. While the overall pressure trends should be reasonable, the local elevation of the column is less useful.

Several thousand more wells have been drilled in the Paradox Basin since 1961, and many had DSTs performed on various formations. The purpose of this study was to review this data and compile a new map of pressure variations across the Mississippian of the basin. This study will improve the understanding of geological constraints on fluid flow within the largely carbonate units of the Paleozoic part of the geologic section. Over much of the basin, the Mississippian section is known as the Leadville Limestone, and it is underlain by Devonian limestone of the Ouray and Elbert Formations (Hintze, 1993). Some oil exploration reports

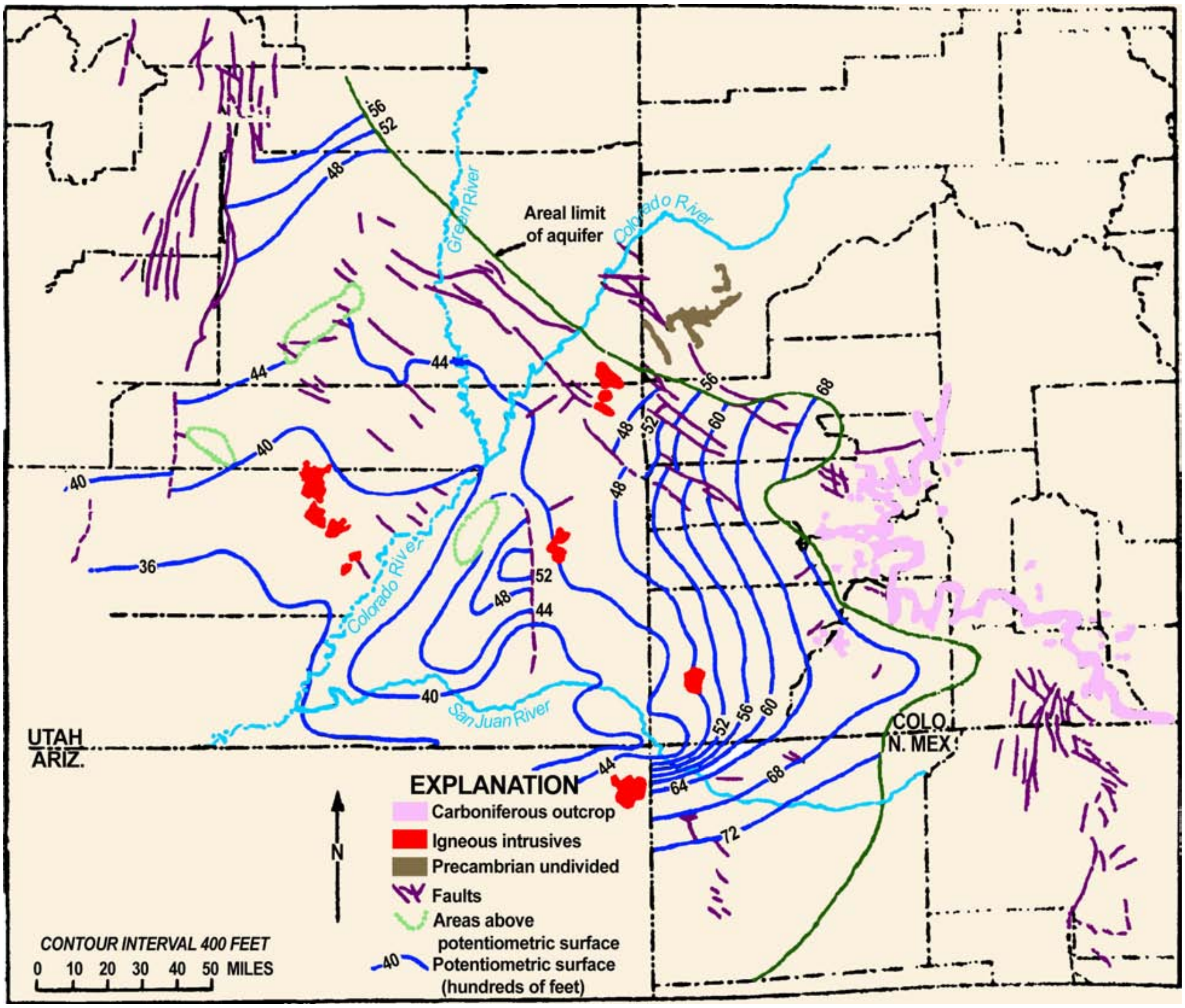


Figure 5. Potentiometric map for the Mississippian derived from oil and gas DST pressure data up to 1961 (from Hanshaw and Hall, 1969).

from wells to the south of the basin refer to the Mississippian Redwall Limestone, and occasionally the name Madison Limestone is used. The Leadville Limestone is overlain by a thin shale (Molas Formation, <150 ft [46 m] thick) at the base of the Pennsylvanian, and this is overlain by the Hermosa Group containing the main oil-producing units of the basin (Paradox Formation). A stratigraphic column for the central Paradox Basin is shown in figure 2.

The Leadville Limestone does not crop out in the Paradox Basin, but it occurs at about 1000 ft (300 m) depth in the Cataract Canyon section of the Colorado River, just downstream of the junction with the Green River (the oldest outcrops in Cataract Canyon are evaporates of the Paradox Formation). On the northeastern margin of the basin, the Leadville Limestone occurs at more than 15,000 ft (4600 m) depth, close to where it is faulted against the Uncompahgre uplift. The carbonate deposition represents a time when there was a stable cratonic platform, prior to the development of a paleoforedeep structure that formed the Paradox Basin. Across much of the eastern half of the basin the Mississippian is overlain by 7000 to 10,000 ft (2100-3000 m) of mostly Pennsylvanian and Permian strata. These cover rocks include low-permeability units of shale, anhydrite, and salt of the Paradox Formation, so there is the potential for significant overpressure in the underlying Mississippian over the eastern half of the basin, and therefore potential for significant lateral variations in fluid pressure here. Simplified maps of the depth to Leadville Limestone (figure 6), and structural contours on the top of the Leadville Limestone (figure 7) show the gross trends of the Laramide uplifts and the regional erosion patterns across the basin. Note that the contours on both maps are based only on picks of the top of the Leadville in oil exploration wells, and there is no account for local incision in canyons or local faulting and folding. East of the Colorado River in the Monument upwarp, and west of the Green River in the San Rafael Swell, the top of the Leadville rises to 5000 ft (1500 m) above sea level (ft asl [m asl]). This elevation is 1000 ft (300 m) above the level of these sections of the Colorado River and the Green River (3800 to 4000 ft asl [1160-1200 m asl]), which are presumably controlling at least the near-surface hydrology in these areas.

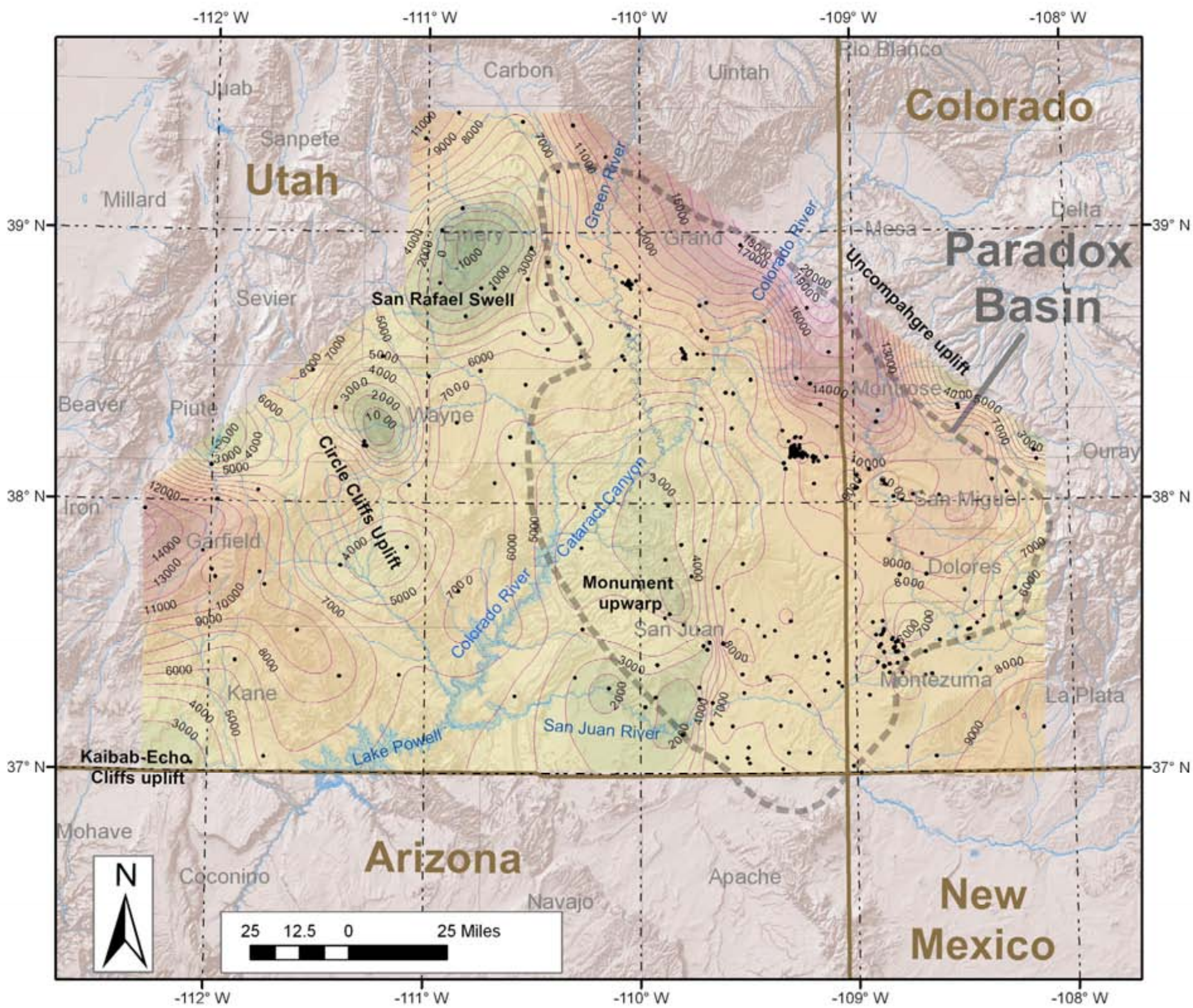


Figure 6. Depth to top of the Mississippian Leadville Limestone derived from oil and gas exploration wells. Note that the contours do not consider local topographic relief between the wells, such as the Colorado River canyon and mountains. Contour interval is 1000 feet.

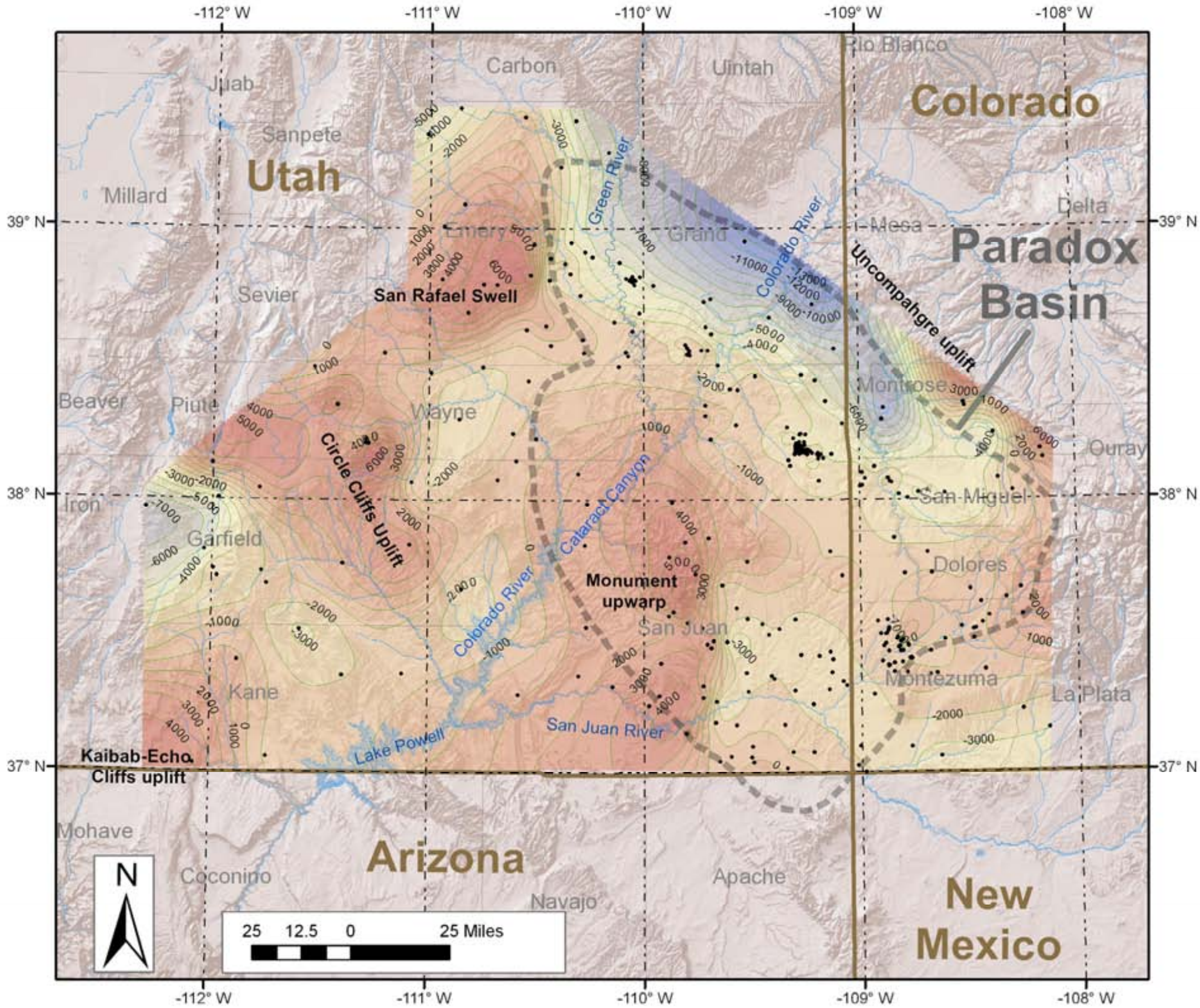


Figure 7. Structural contours on the top of the Leadville Limestone derived from oil and gas exploration wells. Note that the contours do not consider fault offsets and folding between the wells. The contour interval is 1000 feet (relative to sea level). The structural highs correspond to Laramide uplifts.

Data Source and Methodology

About 5000 DST reports compiled by PI/Dwights Plus (IHS Energy Well Data, 2008) were used for this pressure compilation. The "shut-in" pressure values included with this report have been used without further correction for recovery to equilibrium. This is a very noisy dataset, so criteria were applied to screen out obviously inaccurate data. The most common source of error is incomplete pressure recovery because of low permeability, either due to local mud-cake problems or inherently low permeability in the formation (Bredehoeft, 1965; Nelson, 2002). If the shut-in time was less than 30 minutes, or there was no shut-in time recorded, the shut-in pressure was discarded. While the 30-minute threshold sometimes appeared to indicate reliable data for the most permeable formations such as the Leadville Limestone, it was far too short for low-permeability rocks. Even after 240 to 300 minutes, pressures in all reported "salt" formations and some "shale" formations were still clearly far from equilibrium. Most DSTs reported an "initial" and a "final" shut-in pressure, and in such cases the larger of the two values was chosen. The topographically lowest part of the Paradox Basin is the Colorado River, and this should control the minimum pressure in the basin. Any pressure values less than about 70% of hydrostatic pressure beneath the Colorado River were therefore eliminated. Any DSTs that did not identify the formation being tested, or had incomplete depth information, were also eliminated.

As a result of this screening process, between 50 and 75% of the pressure data were removed from further study. To allow further averaging of the pressure data, the Paradox Basin was subdivided into six, one-degree squares (figure 8), and the pressure data were plotted at the elevation of the DST (midpoint of the open interval). This resulted in as few as 27 data points for the Mississippian in the Glen Canyon quadrangle, which has no producing fields, and 614 data points in the Aneth quadrangle. In all, there were 1529 pressure points spread over the six quadrangles. To investigate the vertical pressure trends in each quadrangle, the data were subdivided on the basis of geological time. The Paleozoic was split into the periods Mississippian and older, Pennsylvanian, Permian, and where appropriate, a Mesozoic era was included. The total number of Mississippian and older pressure values is 395, representing less than 10% of the initial DST dataset for the Paradox Basin.

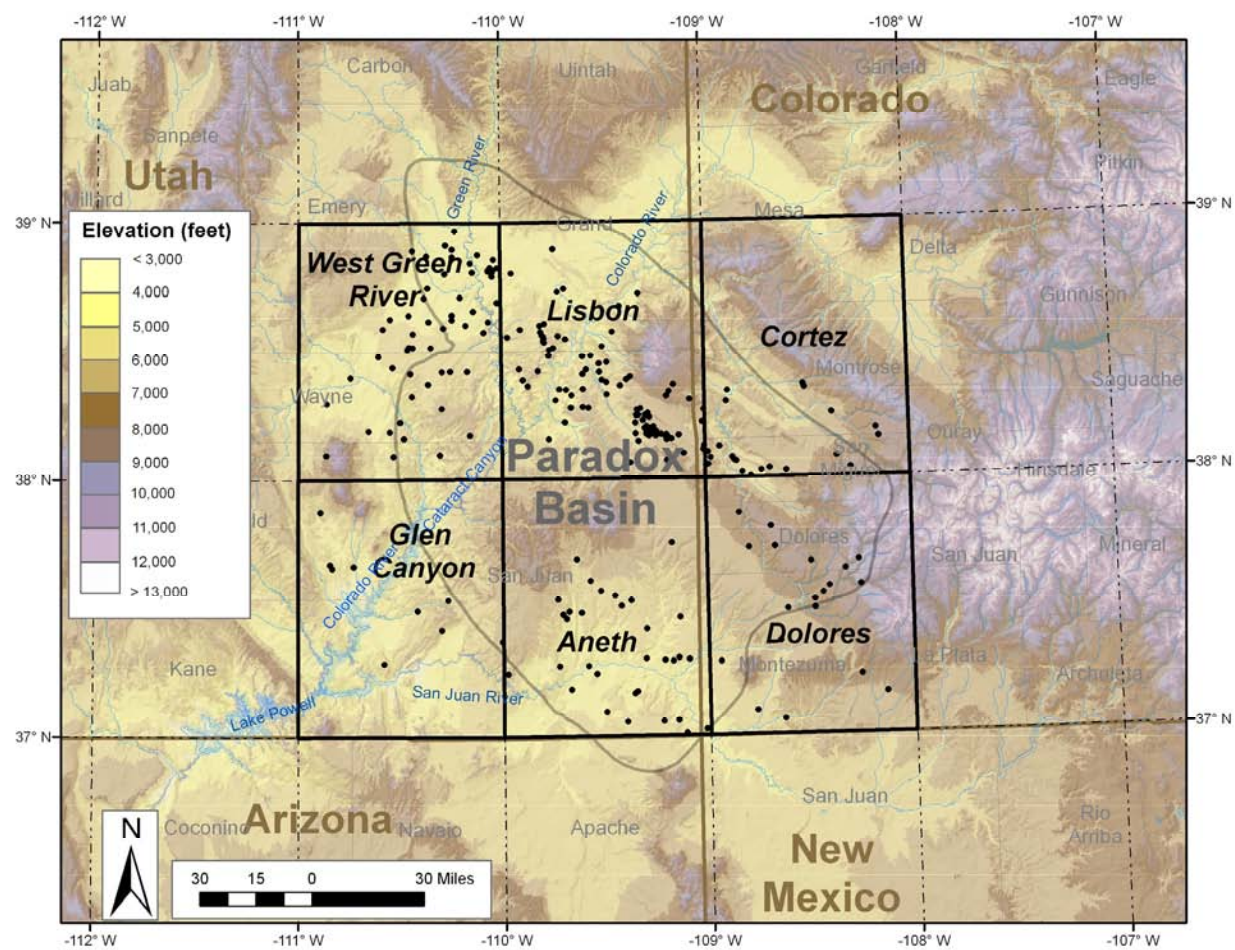


Figure 8. Subdivision of the Paradox Basin into six, one-degree by one-degree quadrangles, for which DST pressure data are consolidated. Dots indicate the distribution of wells which had DST measurements within the Mississippian or older formations.

Pressure Trends by Quadrangle

Figures 9 through 14 show the vertical pressure trends for each quadrangle, and a map of the well locations where the DSTs were made. Sometimes more than one DST is from the same well, and within oil and gas fields, wells are close together and occasionally obscure other well locations. To facilitate comparison between the quadrangles, each graph has the same reference line superimposed on it based on a composite pressure trend for the Mississippian and older strata discussed in a later section. This composite trend line has a slope of 0.47 pounds per square inch/foot (psi/ft [10.6 kPa/m), which is almost 10% above the hydrostatic gradient for fresh water. It is equivalent to a static pressure gradient in a column of water with a salinity of 100,000 to 150,000 mg/kg (J.W. Gwynn, UGS, verbal communication, June 2008) which is reasonable for the Paleozoic section of the Paradox Basin. Shallow ground water in the Paradox Valley, Colorado, has an average dissolved solids concentration of 250,000 mg/kg (Chafin, 2002). However, the springs and geysers near the town of Green River in the north part of the basin have concentrations of 11,000 to about 20,000 mg/kg (Baer and Rigby, 1978; Shipton and others, 2004), so there is probably a gradient in salinity across the basin. Note that the main source of error with DST shut-in pressures is failure to completely come to equilibrium during the test, and for the pressure to be less than actual pressure. These uncertainties are such that the inferred pressure gradient of 0.47 psi/ft (10.6 kPa/m) has an estimated 10% uncertainty.

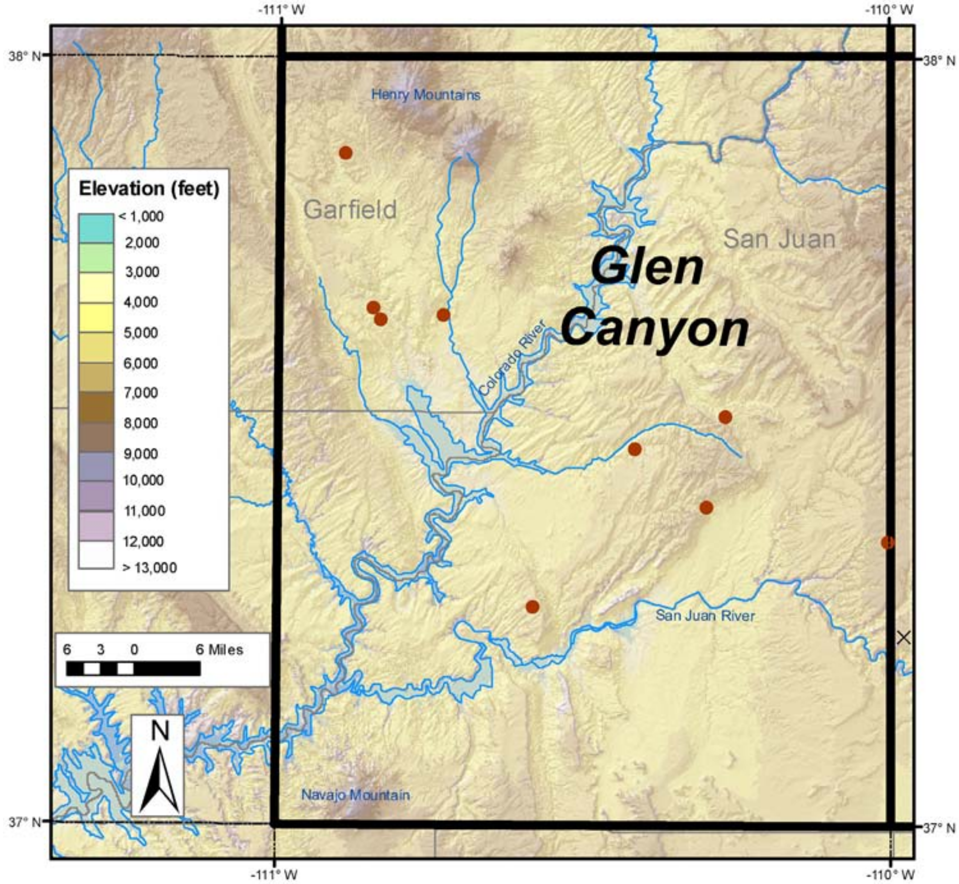
Glen Canyon Quadrangle

The DST pressure data from the Mississippian and older strata are sparse for the Glen Canyon quadrangle (figure 9A), but consistent with a hydrostatic trend when compared with data from the surrounding quadrangles. Although there is a suggestion that the deeper pressures (that is, below sea level) may be less than the regional trend shown on the graph (figure 9B), this is considered unlikely since this area is in the hydrologically lowest part of the Paradox Basin (Colorado River at 3800 ft asl [1160 m]). Pennsylvanian and Permian formations are largely consistent with the one hydrostatic trend extending from near-surface to at least -4000 ft asl (-1200 m asl). Two Pennsylvanian pressure values at shallow depth suggest a locally perched water table near the surface (head at close to 5000 ft asl [1520 m asl]). Both of these pressure points are from wells on the eastern boundary of the quadrangle, and are consistent with a near-surface pressure trend that is more strongly identified on the adjacent quadrangle (Aneth). Hanshaw and Hall (1969) reported that several exploration wells drilled east of Cataract Canyon on the northern end of the Monument upwarp encountered dry conditions down into the Mississippian, which as figure 7 shows, suggests the deep head is at an elevation of less than 4000 to 5000 ft asl (1200-1500 m asl), and consistent with the trend in figure 9.

West Green River Quadrangle

The DST pressure data for the West Green River quadrangle (figure 10A) indicate one linear trend from a shallow water table elevation of about 4000 ft asl (1200 m asl) in the Triassic to the deepest Mississippian at -6000 ft asl (-1800 m asl) (figure 10B). The slope is 0.47 psi/ft (10.6 kPa/m), consistent with saline water. It is likely that the pressure trend is 100

A



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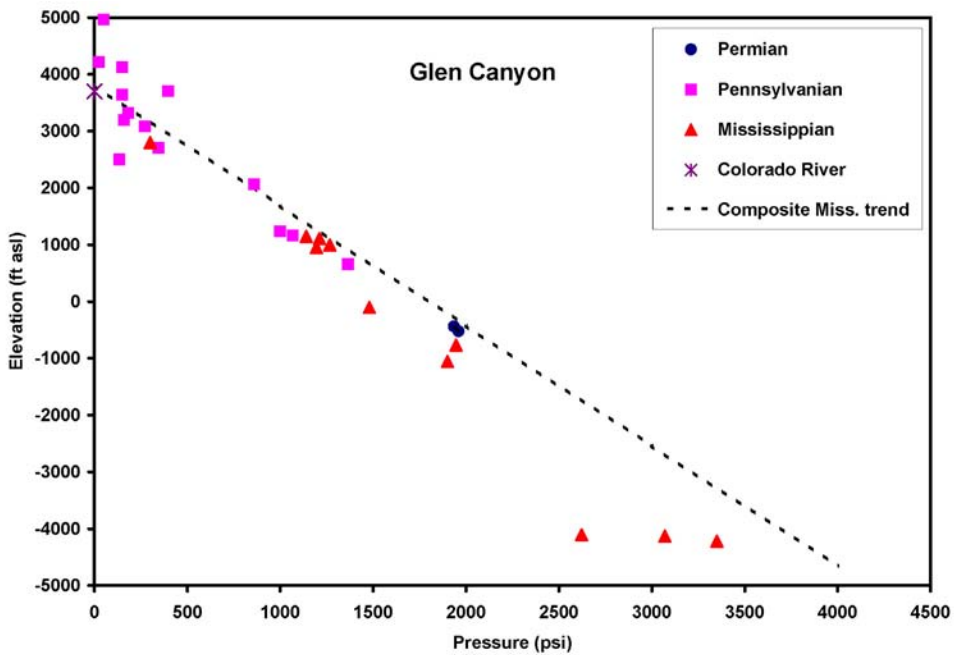


Figure 9. Glen Canyon quadrangle. A – Location of wells within the quadrangle for which DST measurements from the Mississippian (and older) strata have been used in the pressure trend graph in (B). Sometimes more than one DST is available from a well. B – Trend of DST shut-in pressures in the quadrangle. The dashed line is derived from a composite pressure plot discussed in a later figure. Note that the pressures from DSTs tend to be minimums because of possible lack of full equilibrium at the end of the test.

A

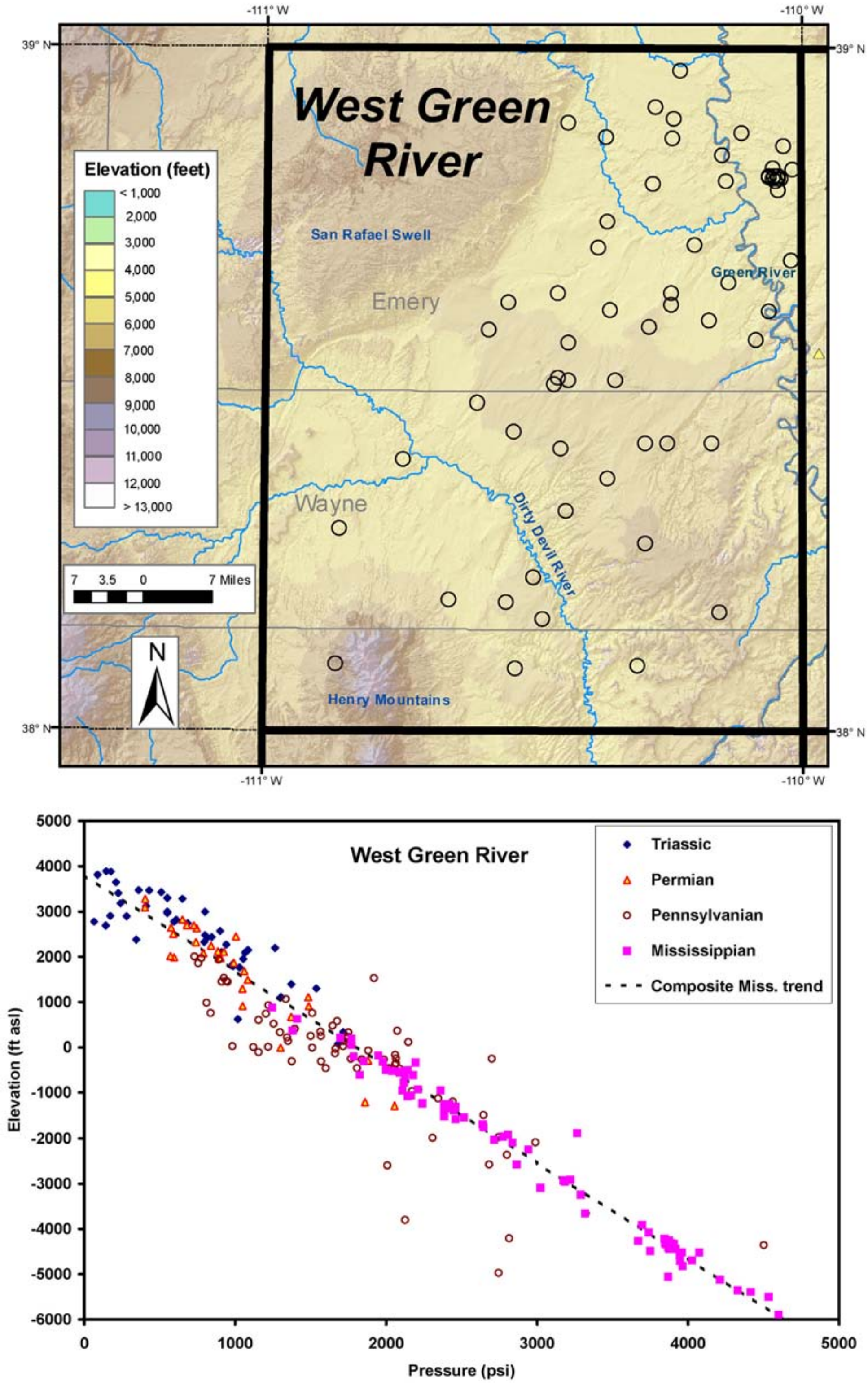


Figure 10. West Green River quadrangle. A – Location of wells within the quadrangle for which DST measurements from the Mississippian (and older) strata have been used in the pressure trend graph in (B). Sometimes more than one DST is available from a well. B – Trend of DST shut-in pressures in the quadrangle. The dashed line is derived from a composite pressure plot discussed in a later figure. Note that the pressures from DSTs tend to be minimums because of possible lack of full equilibrium at the end of the test.

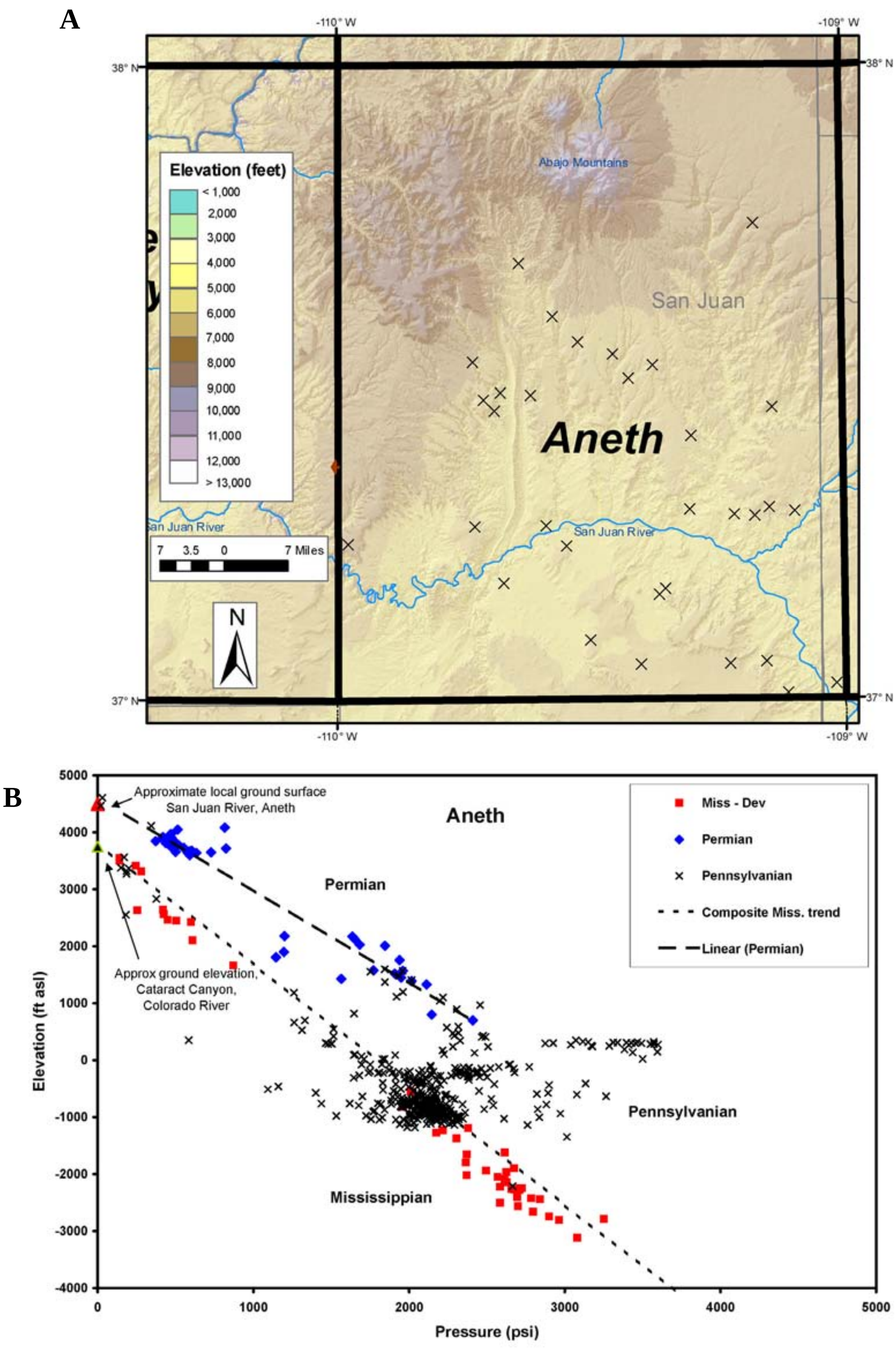


Figure 11. Aneth quadrangle. A – Location of wells within the quadrangle for which DST measurements from the Mississippian (and older) strata have been used in the pressure trend graph in (B). Sometimes more than one DST is available from a well. B – Trend of DST shut-in pressures in the quadrangle. The dashed line is derived from a composite pressure plot discussed in a later figure. Note that the pressures from DSTs tend to be minimums because of possible lack of full equilibrium at the end of the test.

A

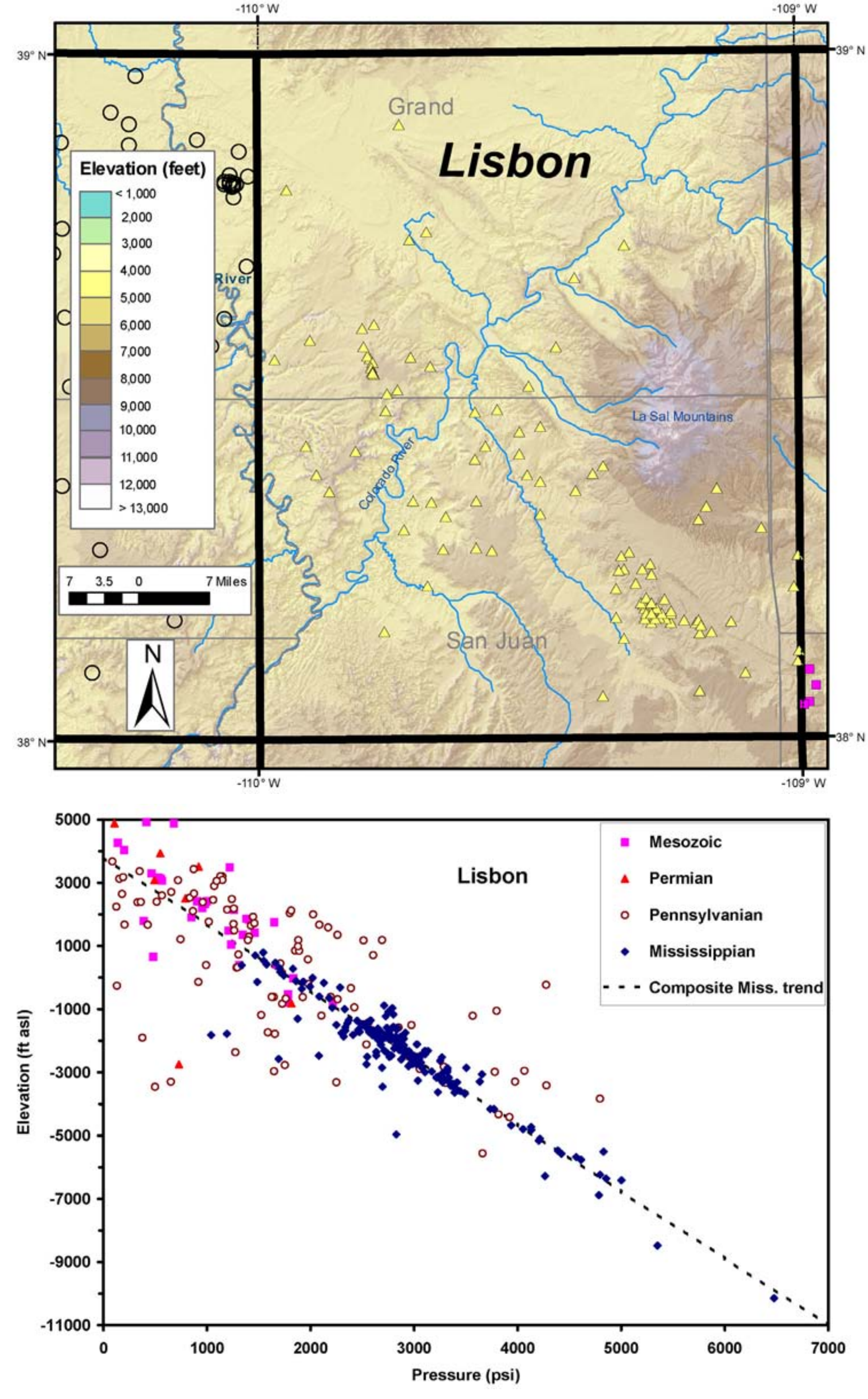


Figure 12. Lisbon quadrangle. A – Location of wells within the quadrangle for which DST measurements from the Mississippian (and older) strata have been used in the pressure trend graph in (B). Sometimes more than one DST is available from a well. B – Trend of DST shut-in pressures in the quadrangle. The dashed line is derived from a composite pressure plot discussed in a later figure. Note that the pressures from DSTs tend to be minimums because of possible lack of full equilibrium at the end of the test.

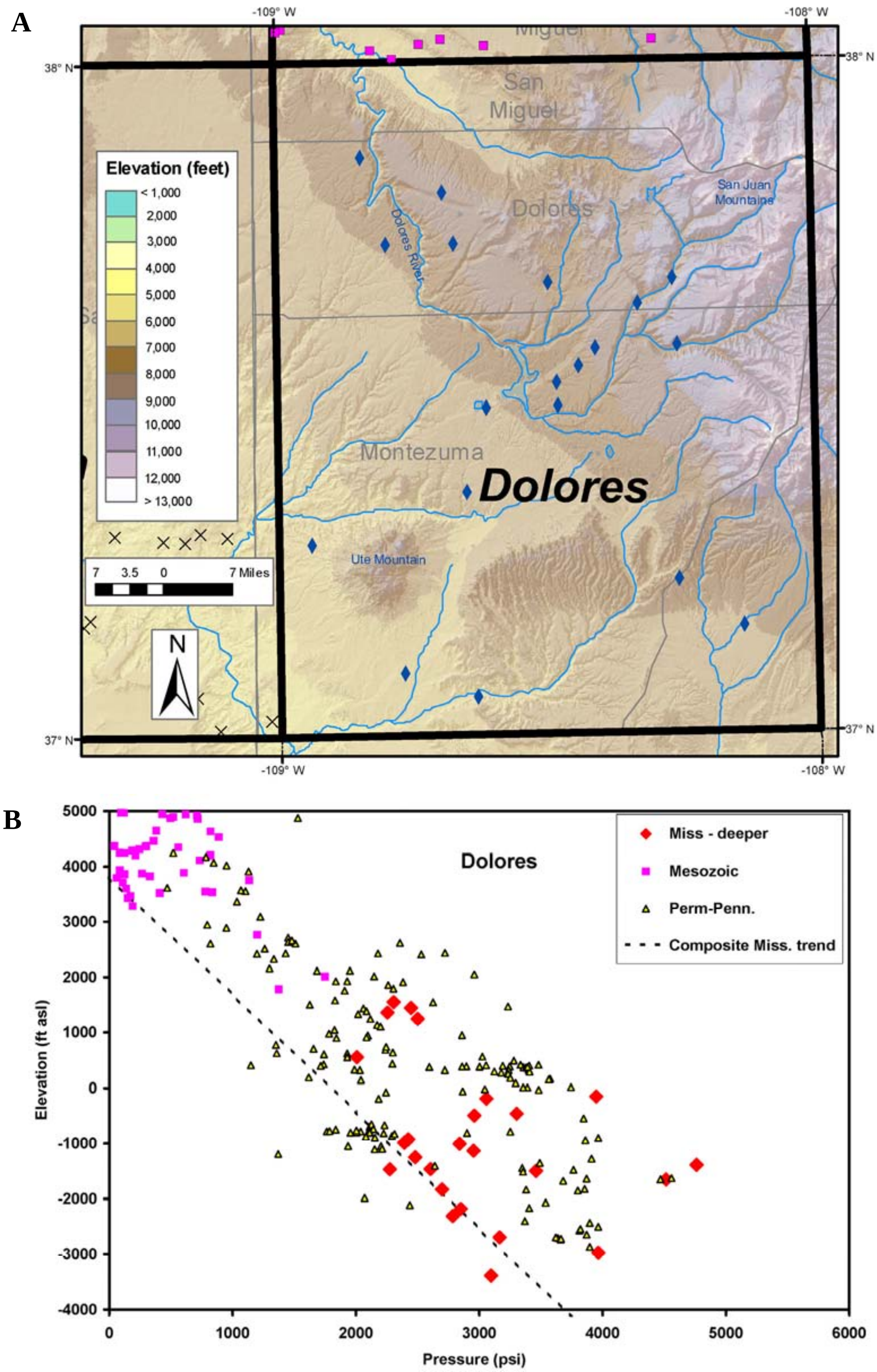
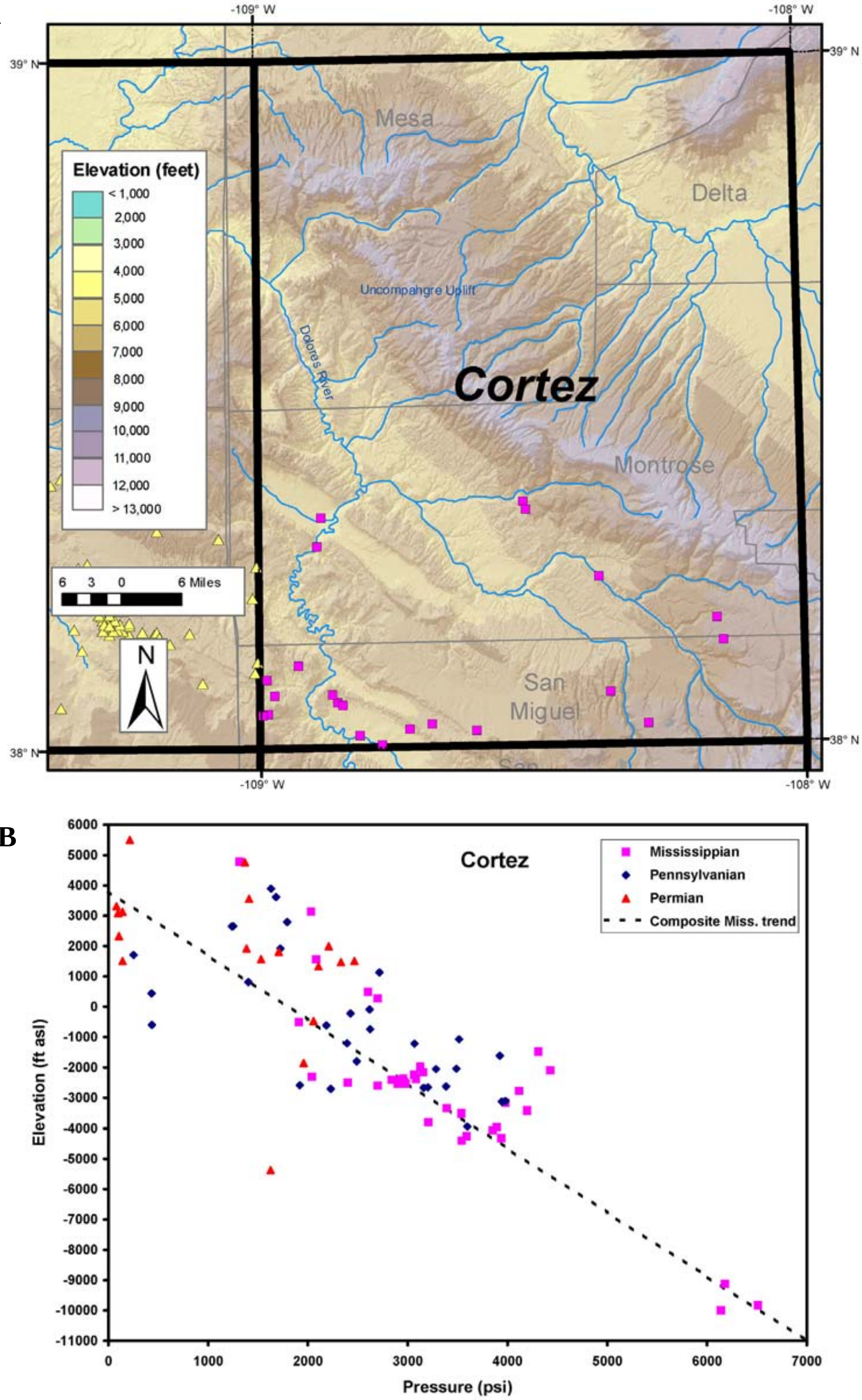


Figure 13. Dolores quadrangle. A – Location of wells within the quadrangle for which DST measurements from the Mississippian (and older) strata have been used in the pressure trend graph in (B). Sometimes more than one DST is available from a well. B – Trend of DST shut-in pressures in the quadrangle. The dashed line is derived from a composite pressure plot discussed in a later figure. Note that the pressures from DSTs tend to be minimums because of possible lack of full equilibrium at the end of the test.

A



B

Figure 14. Cortez quadrangle. A – Location of wells within the quadrangle for which DST measurements from the Mississippian (and older) strata have been used in the pressure trend graph in (B). Sometimes more than one DST is available from a well. B – Trend of DST shut-in pressures in the quadrangle. The dashed line is derived from a composite pressure plot discussed in a later figure. Note that the pressures from DSTs tend to be minimums because of possible lack of full equilibrium at the end of the test.

to 200 psi (690-1380 kPa) higher than the composite trend shown on the graph. This is because of the tendency for DST shut-in pressure to underestimate the actual pressure. In addition, in the northeast corner of the quadrangle immediately east of the Green River, saline water and CO_2 flow to the surface in the form of springs and geyser activity in abandoned wells. These fluids are interpreted to originate from deep within the Paradox Basin (Heath, 2004; Shipton and others, 2004; Allis and others, 2005). The elevation of the springs and overflowing wells is 4050 ft asl (1230 m asl), implying a hydrostatic trend at least 250 ft (75 m) (about 100 psi [690 pKa]) higher than the composite trend on the graph. There may be locally higher pressures within the Pennsylvanian section, with a few pressure points 500 psi (3450 kPa) higher than the regional trend.

Aneth Quadrangle

A relatively large amount of data from the Pennsylvanian exists in the Aneth quadrangle (figure 11A) because of the intensive drilling that has occurred in Greater Aneth and other oil fields in the Blanding sub-basin (figure 1). The Mississippian data are split into two sets: those below sea level (typically > 5000 ft [1500 m] depth) and those above sea level (1000 to 3500 ft asl [300-1100 m asl]). The former are in the eastern half of the quadrangle, the latter are mostly in the western half (Monument upwarp). Both sets of data are consistent with a regionally extensive pressure trend with a head at 3800 ft asl (1160 m asl), the average elevation of the Colorado River in the adjacent Glen Canyon quadrangle. The Pennsylvanian data show more scatter, with most data clustering close to the underlying Mississippian pressure trend (figure 11B). However, there is also clear evidence of overpressures of up to 2000 psi (13,790 kPa) relative to the Mississippian trend. This is likely related to locally lower permeability and hydrocarbon generation within the Pennsylvanian section. The Permian pressure data suggest a hydrostatic gradient with control by surface recharge from a ground elevation of 4500 to 5000 ft asl (1400-1500 m asl). The elevation of the San Juan River near Aneth field is 4400 ft asl (1340 m asl). The Mississippian pressure trend in parts of the quadrangle where it is situated above sea level (mostly western half) is between 500 and 1000 psi (3450-6900 kPa) lower than where the Permian section occurs at a similar elevation (mostly eastern half).

Note that the pressure trends in the higher elevation areas in the north of the quadrangle (Abajo Mountains) are unknown. However, Kirby (2007) reported that ground water levels in the vicinity of the city of Blanding (10 to 15 miles [16-24 km] south of the Abajo Mountains) range between 6400 ft asl (1950 m asl) in the north to 5300 ft asl (1600 m asl) near Blanding. The ground water is “perched” within the Dakota and Burro Canyon Formations (Cretaceous) on top of the underlying Morrison Formation (Upper Jurassic). Recent ground-water wells drilled into the Navajo Sandstone (Lower Jurassic) near Blanding have water levels close to 5400 ft asl (1800 m asl), and encountered good quality drinking water (Loughlin Water Associates, verbal communication, 2008). Both of these Mesozoic aquifers appear to be perched relative to water in Permian and underlying formations.

Lisbon Quadrangle

The Lisbon quadrangle contains more Mississippian pressure data (figure 12A) than the others because of the Mississippian oil and gas fields in the Paradox fold and fault belt (figure 3). The pressure trend (figure 12B) is consistent with, and largely controls (because of the amount of data), the composite pressure trend for the basin. Pennsylvanian pressure data are very scattered, but as in the Aneth quadrangle, there is evidence of local overpressuring by up to about 1000 psi (6900 kPa). The Permian and Mesozoic pressures suggest a trend that is systematically higher than the Mississippian trend, but due to poor data quality, it is unclear whether there is one aquifer trend or locally varying pressure trends with zero-pressure intercepts between 4500 and about 6000 ft asl (1370-1800 m).

Dolores Quadrangle

In the Dolores quadrangle, although some Mississippian DST pressure data (figure 13A) lie close to the composite pressure trend, most data lie at higher pressures (figure 13B). The same higher-pressure pattern occurs in the Permian-Pennsylvanian and the Mesozoic sections. The scatter in the Mesozoic section appears to be smaller than that in the underlying sections, and these data suggest zero-pressure head elevations of between 4000 and 7000 ft asl (1220-2130 m asl). The northeast portion of the quadrangle has higher ground elevations associated with the western flank of the San Juan Mountains, which range up to 14,000 ft asl (4260 m asl) to the east of the quadrangle. The deeper trends (Permian and below) are up to about 2000 psi (13,790 kPa) above the composite pressure trend. The well locations for most of these higher-pressure DSTs are situated in the northeast portion of the quadrangle, suggesting the effects of recharge from the San Juan Mountains to the east.

Cortez Quadrangle

The DST pressure data are scattered in the Cortez quadrangle, although the deep Mississippian pressures are constrained by data from injection wells drilled by the U.S. Bureau of Reclamation near the Dolores River in the Paradox Valley, western Colorado (figure 14A). Here, the three DSTs on figure 14B imply a pressure of 6300 psi (43,400 kPa) at an elevation of -9500 ft asl (-2900 m). This agrees with the undisturbed pressures quoted by Ake and others (2005) of 6235 psi (43,000 kPa) at 9200 ft (2800 m) below sea level for the deep wells in the Paradox Valley. It confirms that the Mississippian near the eastern edge of this quadrangle has pressures similar to the composite trend in the rest of the Paradox Basin farther west. However, there are other Mississippian pressure data up to about 1000 psi (7000 kPa) higher than the composite trend, and two points almost 2000 psi (13,900 kPa) higher. Inspection of the well locations of those DSTs shows them to be in the eastern half of the quadrangle. The same pattern applies to the Pennsylvanian and Permian DSTs. A hydrostatic pressure trend that is an upper boundary to the DSTs would have a zero-pressure intercept of about 8000 ft asl (2400 m asl). The Uncompahgre uplift that diagonally traverses the quadrangle rises to over 9000 ft asl (2700 m asl). Recharge on the uplift may be contributing to the higher pressures apparently occurring in the quadrangle.

Composite Mississippian Pressure Trend

Figure 15 compiles all the Mississippian DST pressure data onto one graph, coded by quadrangle. A linear trend is apparent over an elevation range of 14,000 ft (4300 m), with a slope of 0.47 psi/ft (10.6 kPa/m) as discussed above. To clarify the pattern of a small amount of data plotting at significantly higher pressures than this trend, figure 16 examines the amplitude

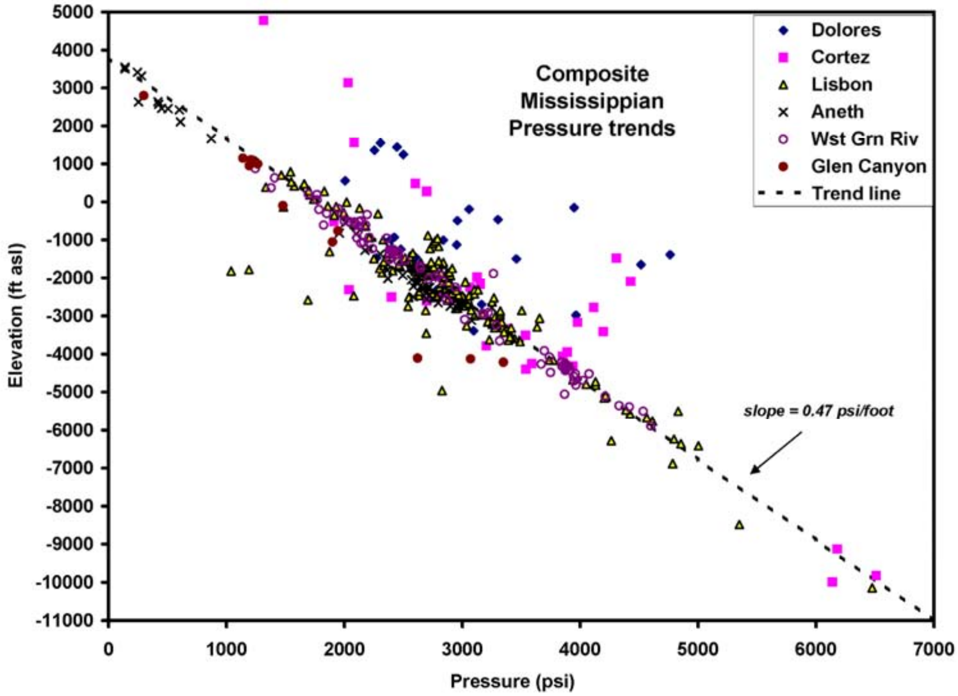


Figure 15. Compilation of DST pressure measurements from all six quadrangles for the Mississippian and older formations. Dashed line is referred to in the text as the "composite pressure trend."

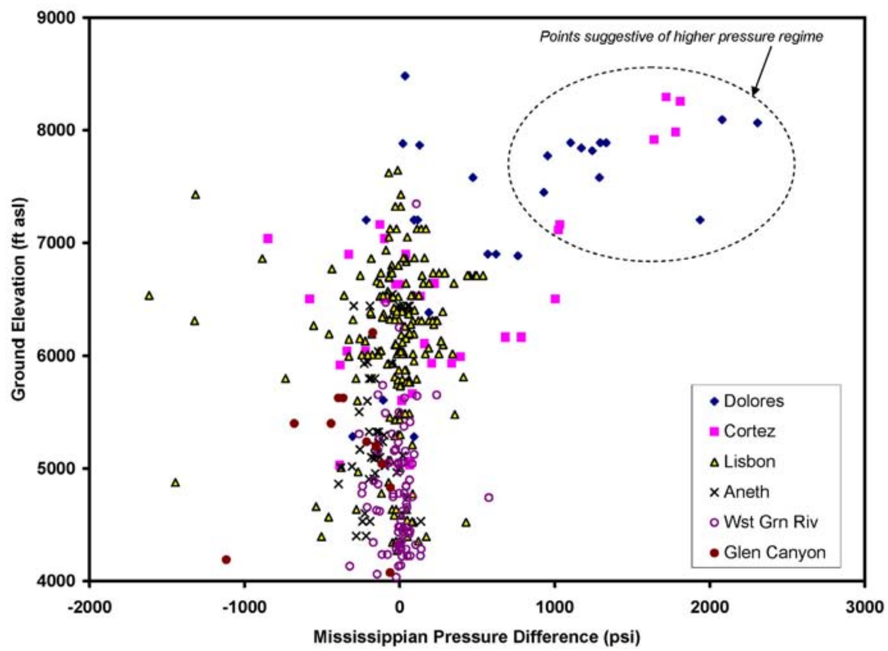


Figure 16. Distribution of pressure differences between the actual DST pressure measurement and the pressure inferred from the composite line for that elevation. The pressure differences are plotted against the ground elevation for the well with the DST. This shows that most of the DSTs in the Dolores and Cortez quadrangles that appear in figure 15 to be at systematically higher pressures, are also at higher ground elevations. They also are in the eastern portions of the two quadrangles, as shown in figure 17.

of the pressure departure from the composite trend against the ground elevation of the well with the DST measurement. This indicates that a systematic pattern of increased pressure departure (that is, higher pressures) with higher ground elevation occurs in the Cortez and Dolores quadrangles. Elsewhere, there is not a significant correlation.

Interpretation

For most of the Paradox Basin, an area of at least 100 by 100 square miles (260 by 260 km^2) including the Glen Canyon, West Green River, Aneth, and Lisbon quadrangles, the Mississippian pressure regime is remarkably uniform, close to hydrostatic, and independent of laterally varying pressure in overlying formations. This implies relatively high permeability, presumably because of interconnected fractures throughout the section and development of karst topography at the top due to subaerial exposure at the end of the Mississippian. The zero-pressure head on this pressure regime varies between 4000 ft asl (1200 m asl) in the north (West Green River quadrangle) and 3800 ft asl (1200 m asl) in the two southern quadrangles. This corresponds to the elevation of the adjacent sections of the Colorado and Green Rivers, which are acting as the pressure control for this entire region.

In the West Green River quadrangle adjacent to the Green River, saline water (11,000 to 20,000 mg/kg total dissolved solids) flows to the surface at several localities, indicating a major discharge point for the basin. Presumably the stretch of the Colorado River south of the junction with the Green River (Cataract Canyon, possibly extending into Glen Canyon/Lake Powell) is also a zone of hydrological connection, and potentially major discharge, for the Mississippian. Any discharge is presumably obscured by the confined, high flow of the Colorado River within the canyon here. Large-scale intrusion of Paradox salt has deformed the canyon (Needles District of Canyonlands National Park), and faults link the northern Monument upwarp to Cataract Canyon (Lewis and Campbell, 1965). The top of the Mississippian section is within about 1000 ft (300 m) of the river level here, when elevations from the wells (figure 6) are interpolated and compared to the river elevation. In the Monument upwarp, the top of the Mississippian section rises to 5000 ft asl (1500 m asl).

Near the eastern margin of the Paradox Basin, the pressure in the Mississippian section increases compared to the regional trend elsewhere by as much as 2000 psi (14,000 kPa) (figure 17). This rise in pressure occurs adjacent to the San Juan Mountains farther east, and presumably represents a major recharge area to the Mississippian and older section. There is no evidence of hydrological transition or boundary zones to the Mississippian section in the north or the west of the studied area. However, there probably are other recharge areas beyond the northwest and west of the six quadrangles studied in this report, perhaps beyond the conventional boundaries of the Paradox Basin as shown in figure 1. Around the north and northeast boundaries, the Mississippian dips beneath the Uinta Basin and may also be faulted against the Uncompahgre uplift, so significant recharge from this direction seems unlikely.

The broad, uniform pressure regime within the Mississippian raises questions about how long it has existed and its implications for past oil and gas migration. Its widespread permeability suggests that it could have been a major fairway for hydrocarbon migration at various times in the past. The top of the Mississippian in the major anticlines in and adjacent to the Paradox Basin (figure 7) is situated above the zero-pressure intercept for the regional pressure trend discussed above. This means that if any fluids are still present, they are likely to be at a low pressure and possibly discontinuous. Depending on the vertical permeability of the

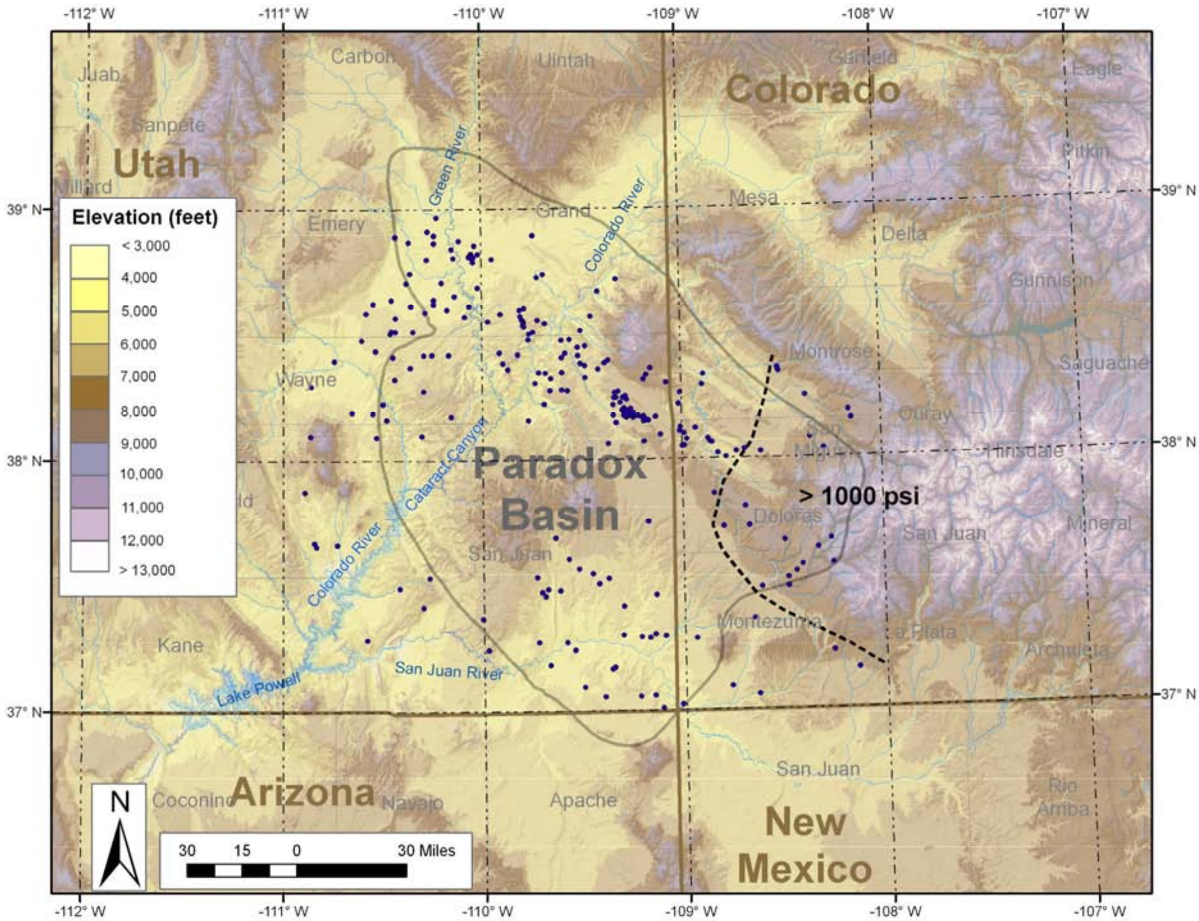


Figure 17. Summary of the region of anomalous pressures identified in figures 15 and 16 for the Mississippian and older rocks of the Paradox Basin. Elsewhere, pressures are close to hydrostatic with a zero-pressure intercept of 3800 to 4000 ft asl.

overlying strata, the Mississippian could be air-filled (dry) as reported by Hanshaw and Hill (1969) for some wells on the Monument upwarp. However, this may not have been the case several million years ago. Down-cutting by the Colorado River system has hydrologically intercepted the Mississippian section. Using characteristic incision rates of 1 foot/thousand years (0.6 to 1.6 ft [0.18-0.5 m] per 1000 years – see Davis and others, 2001; Hanks and others, 2001; Marchetti and Cerling, 2001; Willis and Biek, 2001; Pederson and others, 2002), several million years ago there would have been several thousand feet more of section overlying and potentially sealing the Mississippian. Today's relative underpressure of the Mississippian relative to the Pennsylvanian and Permian as seen in the Aneth quadrangle would not have been present, and the hydrodynamic gradient could have been in a different direction. That is, the large-scale fluid flow that is inferred to be occurring today towards the Colorado River would not have been occurring, and the Mississippian would have been fully saturated within the Paradox Basin, and could have held significant quantities of oil and gas within the structural highs.

TECHNOLOGY TRANSFER

The UGS is the Principal Investigator and prime contractor for the Leadville Limestone project, described in this report. All maps, cross sections, lab analyses, reports, databases, and other deliverables produced for the project will be published in interactive, menu-driven digital (Web-based and compact disc) and hard-copy formats by the UGS for presentation to the petroleum industry. Syntheses and highlights will be submitted to refereed journals, as appropriate, such as the *American Association of Petroleum Geologists (AAPG) Bulletin* and *Journal of Petroleum Technology*, and to trade publications such as the *Oil and Gas Journal*. This information will also be released through the UGS periodical *Survey Notes* and be posted on the UGS Paradox Basin project Web page.

The technology-transfer plan includes the formation of a Technical Advisory Board and a Stake Holders Board. These boards meet annually with the project technical team members. The Technical Advisory Board advises the technical team on the direction of study, reviews technical progress, recommends changes and additions to the study, and provides data. The Technical Advisory Board is composed of Leadville field operators and those who are actively exploring for Leadville hydrocarbons in Utah and Colorado. This board ensures direct communication of the study methods and results to the operators. The Stake Holders Board is composed of groups that have a financial interest in the study area including representatives from the State of Utah (School and Institutional Trust Lands Administration, and Utah Division of Oil, Gas and Mining) and the federal government (Bureau of Land Management). The members of the Technical Advisory and Stake Holders Boards receive all semi-annual technical reports, copies of all publications, and other material resulting from the study. Board members also provide field and reservoir data.

Project materials, plans, objectives, and results were displayed at the UGS exhibit booth during the AAPG Rocky Mountain Section (RMS) meeting, October 7-9, 2007, in Snowbird, Utah. Four UGS scientists staffed the display booth at this event. Project displays will be included as part of the UGS booth at professional meetings throughout the duration of the project.

An abstract identifying potential oil-prone areas based on hydrocarbon shows using epifluorescence techniques was submitted and accepted for presentation at the July 2008 AAPG RMS meeting at Denver, Colorado.

Utah Geological Survey *Survey Notes* and Web Site

The UGS publication *Survey Notes* provides non-technical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision-makers, and the public. *Survey Notes* is published three times yearly. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged. The UGS maintains a database that includes those companies or individuals specifically interested in the Leadville project or other DOE-sponsored UGS projects. They receive *Survey Notes* and notification of project publications and workshops.

The UGS maintains a Web site on the Internet, http://geology.utah.gov. The UGS site includes a page under the heading *Oil, Gas, Coal, & CO_2*, which describes the UGS/DOE cooperative studies past and present (PUMPII, Paradox Basin [two projects evaluating the

Pennsylvanian Paradox Formation], Ferron Sandstone, Bluebell field, Green River Formation), and has a link to the DOE Web site. Each UGS/DOE cooperative study also has its own separate page on the UGS Web site. The Leadville Limestone project page, http://geology.utah.gov/emp/leadville/index.htm, contains (1) a project location map, (2) a description of the project, (3) a reference list of all publications that are a direct result of the project, (4) poster presentations, and (5) semi-annual technical progress reports.

Presentation

The following presentation was made during the reporting period as part of the technology transfer activities:

> "New Techniques for New Discoveries – Results from the Lisbon Field Area, Paradox Basin, Utah" by David Seneshen, T.C. Chidsey, C.D. Morgan, and M.D. Vanden Berg, presented at the AAPG Rocky Mountain Section meeting in Snowbird, Utah, October 8, 2007. This presentation included an overview of the Leadville project and the results of the Lisbon-area surface geochemical survey.

Project Publications

Chidsey, T.C., Jr., Morgan, C.D., and Eby, D.E., 2007, The Mississippian Leadville Limestone exploration play, Utah and Colorado: exploration techniques and studies for independents – semi-annual technical progress report for the period April 1, 2007 to September 30, 2007: U.S. Department of Energy, DOE/BC15424-8, 28 p.

Seneshen, D.M., Chidsey, T.C., Jr., Morgan, C.D., and Vanden Berg, M.D., 2007, New techniques for new discoveries – results from the Lisbon field area, Paradox Basin, Utah [abs]: American Association of Petroleum Geologists, Rocky Mountain Section Meeting Official Program, p. 55-56.

We also submitted a final manuscript on the Leadville surface geochemical survey, "New Techniques for New Discoveries – Surface Geochemical Results from the Lisbon Field Area, Paradox Basin, Utah," for inclusion in the Rocky Mountain Association of Geologists 2008 guidebook titled "Petroleum Geology of the Paradox Basin."

Core Workshop

A Leadville short course, "Depositional Environments, Diagenesis, and Hydrothermal Alteration of the Mississippian Leadville Limestone Reservoir, Paradox Basin, Utah: A Core Workshop," was presented at the AAPG RMS meeting. This workshop was for geoscientists with interests in exploration and development of shallow-shelf carbonate reservoirs. It was designed for geoscientists who wished to examine a large collection of carbonate core (both limestone and dolomite) presented within lithofacies, diagenetic, and petrophysical context. Representative core from Utah's Lisbon field was examined. The core workshop was organized into two topical sessions: Leadville Facies/Fabrics and Leadville Burial Overprint. Participants performed a series of group exercises using core, geophysical well logs, and photomicrographs from thin sections. These sessions included describing reservoir versus non-reservoir lithofacies; determining diagenesis, hydrothermal alteration, and porosity from core; recognizing barriers and baffles to fluid flow; correlating core to geophysical well logs; and identifying potential completion zones. Following the core sessions, we presented a summary lecture on our Leadville diagenetic/alteration interpretation based on geochemical analysis and petrographic techniques. Twenty-two geologists attended the course. We were asked to present the course again, sponsored by the Petroleum Technology Transfer Council and the Rocky Mountain Association of Geologists, at the U.S. Geological Survey's Denver Core Research Center, May 23, 2008.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

1. The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from seven fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. Most Leadville oil and gas production is from basement-involved structural traps. All of these fields are currently operated by independent producers. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored. Only independent producers continue to hunt for Leadville oil targets in the region.

2. Shut-in DST pressure data from petroleum exploration and development wells in the Paradox Basin were used to establish the major hydrodynamic trends, especially within the Mississippian (395 DSTs).

3. With the exception of the eastern edge of the basin (western flanks of the San Juan Mountains), there is a single pressure regime for the Mississippian, having a composite pressure gradient of 0.47 pounds per square inch/foot (10.6 kPa/m) over an elevation range of +4000 to -10,000 ft asl (1200 to -3000 m asl). This remarkably uniform pressure regime over an area of at least 100 by 100 square miles (260 by 260 km^2) indicates relatively high permeability within the Mississippian.

4. The pressure gradient is about 10% above hydrostatic for fresh water, but is consistent with the density of relatively saline water having a total dissolved solids concentration of 100,000 to 150,000 mg/kg. The head is between 3800 and 4000 ft asl (1160 and 1200 m asl), and coincides with the elevation of the lower Green River and Cataract Canyon section of the Colorado River where they traverse the basin.

5. It appears that the Mississippian and older reservoirs across most of the Paradox Basin are in good hydrological communication with the Colorado River system, perhaps because they are within about 1000 ft (300 m) of the surface beneath Cataract Canyon. This large-scale hydrological connection between the surface and the Mississippian maybe a geologically recent occurrence.

6. Consideration of the rate of incision by the Colorado River system suggests that the Mississippian could have been hydrologically isolated and fully saturated several million years ago, and could have held significantly greater quantities of oil and gas.

ACKNOWLEDGMENTS

Funding for this research was provided as part of the Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program of the U.S. Department of Energy, National Energy Technology Laboratory, Tulsa, Oklahoma, contract number DE-FC26-03NT15424. The Contracting Officer's Representative is Virginia Weyland. Support was also provided by the Utah Geological Survey (UGS) and Eby Petrography & Consulting, Inc., Denver, Colorado.

James Parker, Sharon Wakefield, and Cheryl Gustin of the UGS gathered data, drafted figures, and prepared maps; Cheryl Gustin formatted the manuscript. This report was reviewed by David E. Tabet and Michael Hylland of the UGS.

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